High-p_T pion associated with dilepton and heavy quarkonia production in pp collisions at RHIC and LHC

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Outline

1. Motivation
2. Color Dipole Description of Drell-Yan process
   - $pp \to \gamma^*/Z^0 \to \ell^+\ell^-$
   - $pA \to \gamma^*/Z^0 \to \ell^+\ell^-$
   - Dilepton - hadron correlations
3. Color Dipole Description of Quarkonium Production
4. Conclusions and Outlook

Introduction

Drell-Yan and heavy quarkonia studies

- Drell-Yan (DY) in $pp/pA/AA$ collisions is an excellent tool for the investigations of strong interaction dynamics in an extended kinematical range of energies and rapidities.
  - DY in *pp* allows to test the Standard Model (SM) and search for New Physics beyond the SM.
  - In *pA* it is used to investigate the onset of initial-state effects.
- Quarkonia production in pp/pA, as well as high-p_T forward particle production in *pA*, are traditionally very important probes of QCD dynamics e.g. QCD factorisation, gluon resummation, higher order PT and non-PT effects, medium properties, CGC etc.
  - In *pp* heavy quark masses provide hard scale for study of production mechanisms in pQCD (factorisation breaking, CS vs. CO,...)
  - $c\bar{c}$ are special - m_c is at the boundary between pQCD and soft QCD.

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Color dipole description of Drell-Yan process

Frame-dependent description of Drell-Yan process

B. Kopeliovich, hep-ph/9609385: *(in DY) . . . statement that the annihilating quark and antiquark belong to the beam and to the target respectively . . . is not Lorentz invariant.*

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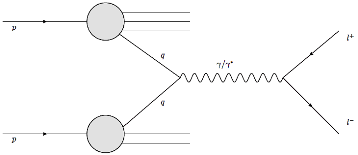

- In the target rest frame, the DY process looks like fragmentation of a projectile quark into a dilepton via bremsstrahlung of a heavy photon

- Partonic fluctuation lifetime is enhanced $\Delta\tau_{lab}/ \approx \sqrt{s}/m_p \times \Delta\tau_{cms}$.
- The photon can be radiated before or after the quark scattering.

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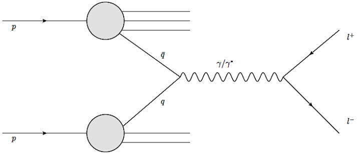

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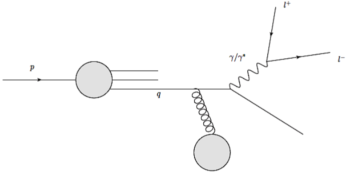

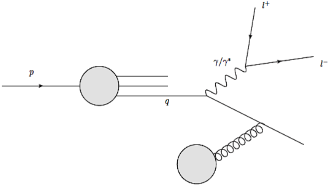

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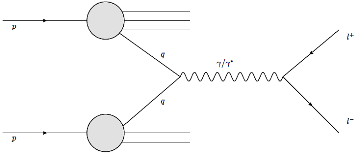

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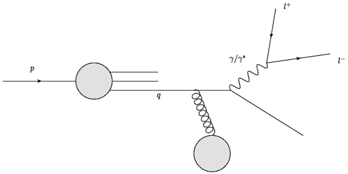

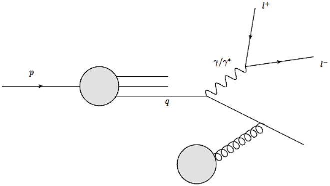

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Color dipole description of DY process

J. Raufeisen *et al.*, Phys. Rev. D **66**, 034024 (2002):

- *In the kinematical region where $\sqrt{s} \gg$ all other scales (e.g. m_c, m_b), the DY process can be formulated in the target rest frame in terms of the same color dipole cross section which is used in low-x DIS [1]:*

$$\boxed{\frac{d\sigma(qN\to\gamma^* X)}{d\ln\alpha} = \int d^2\rho\, \left|\Psi_{\gamma^* q}(\alpha,\rho)\right|^2\, \sigma^N_{q\bar{q}}(\alpha\rho, x)}$$

$\Psi_{\gamma^* q}(\alpha,\rho)$ – LC wave function, gives rate of $q\to\gamma^* q$ EM radiation, is PT calculable.
$\sigma^N_{q\bar{q}}$ – dipole cross section is of NP origin, comes from phenomenology (GBW [2] *etc.*)
α – LC momentum fraction of parent quark taken away by γ^*.
ρ – transverse separation between γ^* and final quark.

$$\frac{d^2\sigma(pN\to\ell^+\ell^- X)}{dM^2 dx_F} = \frac{\alpha_{em}}{3\pi M^2}\frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_{f=1}^{N_f} Z_f^2\left[q_f\left(\frac{x_1}{\alpha},\mu^2\right)+\bar{q}_f\left(\frac{x_1}{\alpha},\mu^2\right)\right]\frac{d\sigma(qN\to\gamma^* X)}{d\ln\alpha}$$

$x_1 = \frac{2\,P_2\cdot p}{s}$, $x_2 = \frac{2\,P_1\cdot p}{s}$, $s = (P_1+P_2)^2$, $p^2 = M^2 \equiv M^2_{\ell\bar{\ell}}$, $x_F = x_1 - x_2 = 2\,p_L/\sqrt{s}$
$\mu^2 = (1-x_1)M^2$ – hard scale at which the projectile parton distribution q_f is probed.

[1] N. N. Nikolaev and B. G. Zakharov, Z. Phys. C49, 607 (1991)
[2] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D 59, 014017 (1999); *ibid* 60, 114023 (1999); PRL 86, 596 (2001)

Color dipole approach @ large M: $pp \to \gamma^*/Z^0 \to \ell^+\ell^-$

- Quark bremsstrahlung of a virtual gauge boson G^* ($G = \gamma, Z^0$)

$$\frac{d\sigma(pp \to [G^* \to \ell^+\ell^-]X)}{d^2p_T dM^2 d\eta} = \mathcal{F}_G(M)\, \frac{d\sigma(pp \to G^* X)}{d^2p_T d\eta}\,, \qquad G = \gamma^*/Z^0$$

where
$$\mathcal{F}_\gamma(M) = \frac{\alpha_{em}}{3\pi M^2}\,, \qquad \mathcal{F}_Z(M) = \mathrm{Br}(Z^0 \to \ell^+\ell^-)\rho_Z(M)$$

and

$$\rho_Z(M) = \frac{1}{\pi}\,\frac{M\Gamma_Z(M)}{(M^2 - m_Z^2)^2 + [M\Gamma_Z(M)]^2}\,, \qquad \Gamma_Z(M)/M \ll 1\,,$$

with

$$\Gamma_Z(M) = \frac{\alpha_{em} M}{6\sin^2 2\theta_W}\left(\frac{160}{3}\sin^4\theta_W - 40\sin^2\theta_W + 21\right),$$

- In calculations we take m_u=m_d=m_s=0.14GeV, m_c=1.4 GeV, m_b=4.5 GeV, and use the CT10 NLO parametrization[1] for the projectile quark PDFs with the factorization scale μ_F=M.

[1] H. L. Lai *et al.*, Phys. Rev. D **82**, 074024 (2010).

Color dipole cross section parametrizations

GBW: K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **59**, 014017 (1999); 60, 114023 (1999); PRL **86**, 596 (2001) $\sigma^N_{q\bar{q}}(\rho,x) = \sigma_0\left[1-\exp(-\frac{\rho^2 Q_s^2(x)}{4})\right]$, $Q_s^2(x) = Q_0^2\left(\frac{x_0}{x}\right)^\lambda$

BGBK: J. Bartels, K. Golec-Biernat and H. Kowalski, Phys. Rev. D **66**, 014001 (2002)

$$\sigma^N_{q\bar{q}}(\rho,x)=\sigma_0\left[1-\exp\left(-\frac{\pi^2}{\sigma_0 N_c}\rho^2\alpha_s(\mu^2)xg(x,\mu^2)\right)\right],\ \frac{\partial xg(x,\mu^2)}{\partial\ln\mu^2}=\frac{\alpha_s(\mu^2)}{2\pi}\int_x^1 dz P_{gg}(z)\frac{x}{z}g(\frac{x}{z},\mu^2)$$

IP-sat: H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74**, 074016 (2006); G. Watt and H. Kowalski, ibid D **78**, 014016 (2008)

$$\sigma^N_{q\bar{q}}(\rho,x)=2\int d^2b\left[1-\exp\left(-\frac{\pi^2}{2N_c}\rho^2\alpha_s(\mu^2)xg(x,\mu^2)T_G(\mathbf{b})\right)\right],\ T_G(\mathbf{b})=(1/2\pi B_G)\exp(-b^2/2B_G)$$

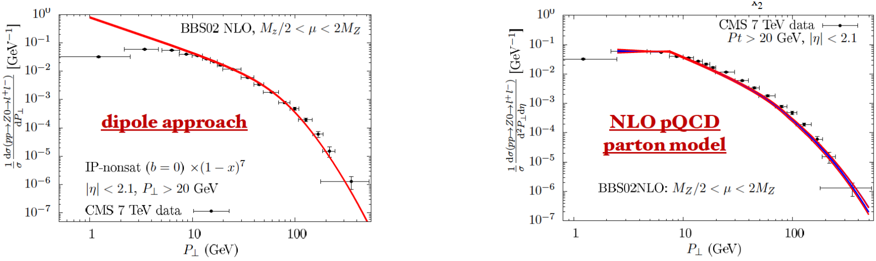
- Testing the sensitivity to $\sigma^N_{q\bar{q}}$ parametrizations via $\sigma(pp\to Z^0+X)$:

$\sqrt{s}$ (TeV)	GBW	BGBK	IP-SAT	DATA (nb)
7	0.950	1.208	0.986	0.937 ± 0.037 [1] 0.974 ± 0.044 [2]
8	1.083	1.427	1.183	1.15 ± 0.37 [3]
14	1.852	2.797	2.514	–

[1] ATLAS: G. Aad *et al.* (ATLAS Collaboration), JHEP **12**, 060 (2010).
[2] CMS: V. Khachatryan *et al*. (CMS Collaboration), JHEP **10**, 132 (2011).
[3] CMS: V. Khachatryan *et al*. (CMS Collaboration), Phys. Rev. Lett. **112**, 191802 (2014)

DY: Color dipole approach vs. NLO pQCD calculations

- CMS data on $pp \to Z^0 \to \ell^+\ell^-$

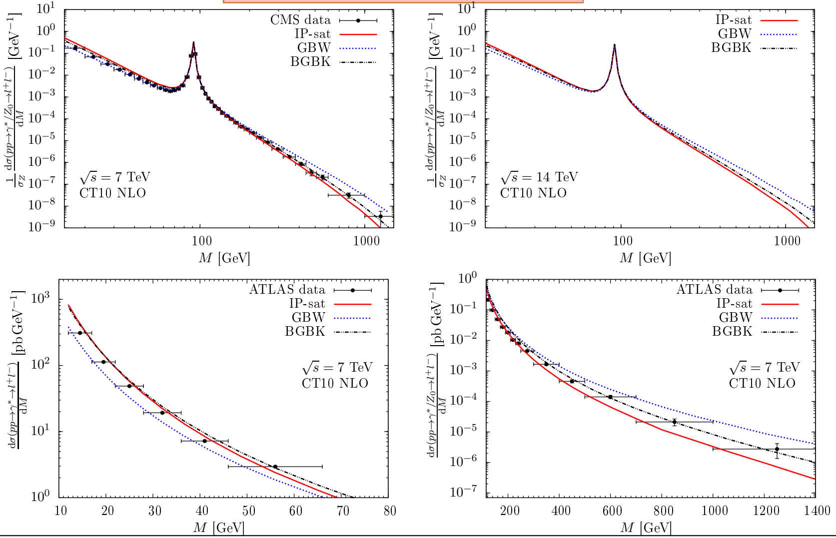


- Confirms previous observation [1,2] that dipole approach effectively accounts for higher order pQCD corrections.
- Fails outside the region of its validity (at low p_T).

[1] J. Raufeisen, J.-C. Peng and G. C. Nayak, Phys. Rev. D **66**, 034024 (2002);
[2] M. B. Johnson *et al.* Phys. Rev. C **75**, 035206 (2007); M. B. Johnson *et al.* ibid C **75**, 064905 (2007).

$pp \to \gamma^*/Z^0 \to \ell^+\ell^-$ @ LHC

E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

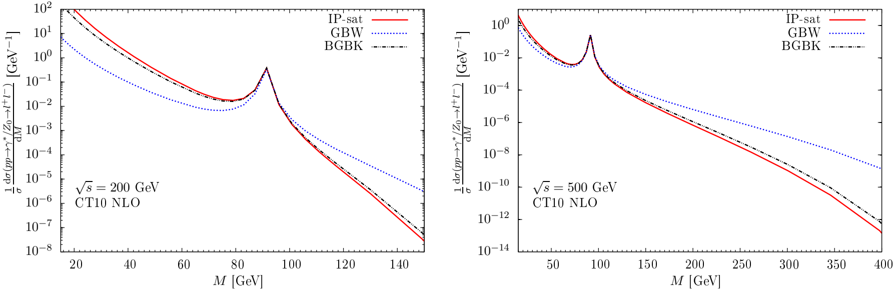


ATLAS: G. Aad *et al.* (ATLAS Collaboration), JHEP **1406**, 112 (2014), Phys. Lett. B **725** 223 (2013).

CMS: V. Khachatryan *et al*. (CMS Collaboration), Eur. Phys. J. **75**, 147 (2015).

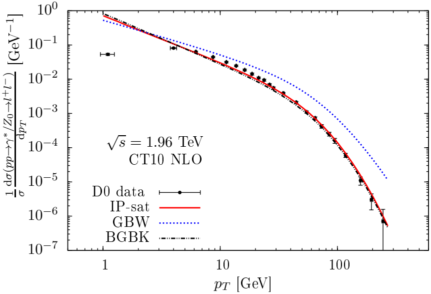
$pp \to \gamma^*/Z^0 \to \ell^+\ell^-$ at large M @ RHIC

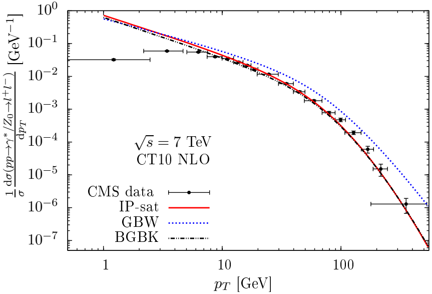
E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

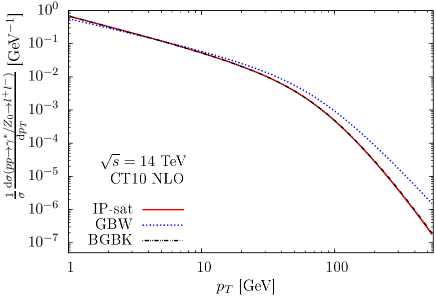


- Dilepton invariant mass spectra at large M are sensitive to different dipole cross section $\sigma^N_{q\bar{q}}$ parametrizations.

DY: Color dipole approach @ Tevatron and LHC







E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

Three different parametrizations of dipole cross section used:

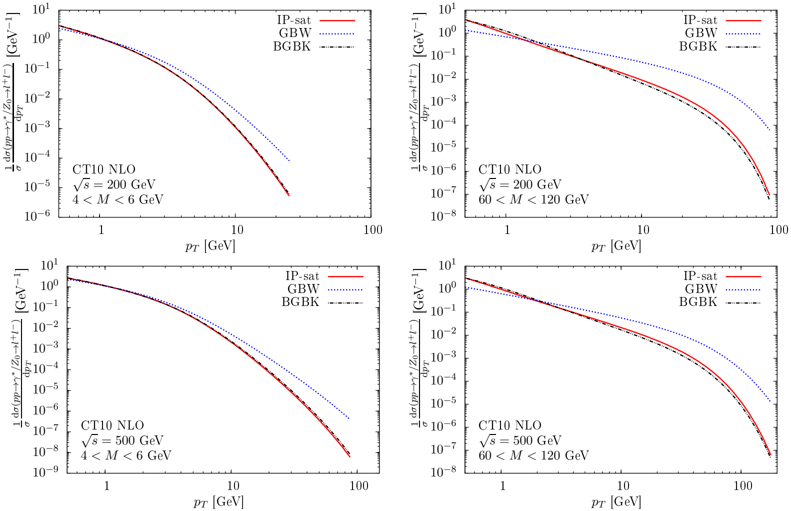
IP-sat: H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74**, 074016 (2006); G. Watt and H. Kowalski, Phys. Rev. D **78**, 014016 (2008).

GBW: K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **59**, 014017 (1999); 60, 114023 (1999); PRL **86**, 596 (2001).

BGBK: J. Bartels, K. Golec-Biernat and H. Kowalski, Phys. Rev. D **66**, 014001 (2002).

Color dipole predictions for DY@RHIC

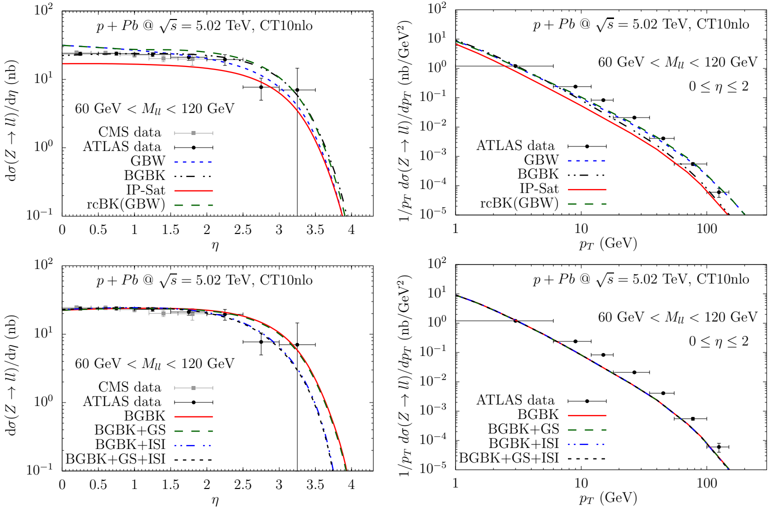
E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)



- Sensitive to different parametrizations of dipole cross section $\sigma^N_{q\bar{q}}$

Color dipole approach @ LHC: $pPb \to \gamma^*/Z^0 \to \ell\bar{\ell}$

E. Basso *et. al.*, arXiv:1603.01893 [hep-ph]



ATLAS: G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. C**92**, 044915 (2015).

CMS: V. Khachatryan *et al*. (CMS Collaboration), arXiv:1512.06461 [hep-ex].

Dilepton - hadron correlations

- In both *pA* and *pp* collisions DY production is accompanied by hadrons - fragments of the quark which radiated γ^*.

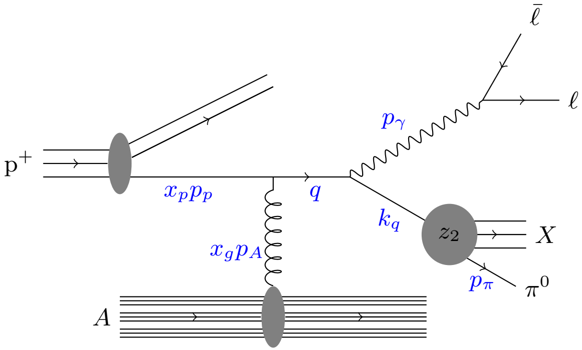


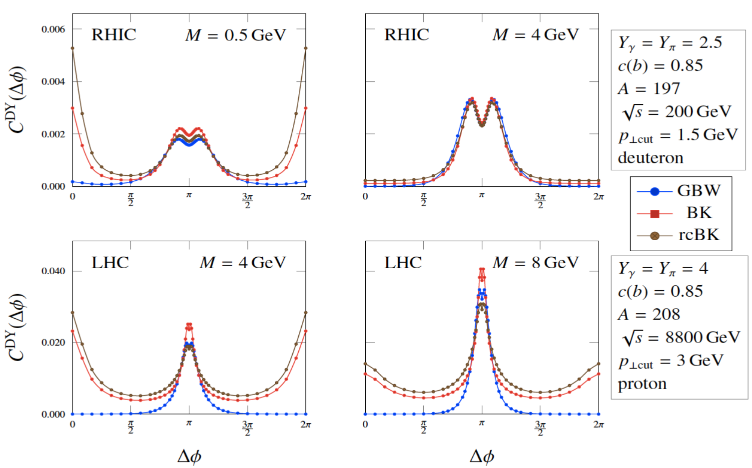
Figure from A. Staśto *et al.*, Phys. Rev. D **86**, 014009 (2012).

$\Rightarrow$ Study γ^*-h azimuthal correlations

For γ-h correlations see: J. Jalilian-Marian and A. H. Rezaeian, Phys. Rev. D **86**, 034016 (2012), A. H. Rezaeian, ibid, 094016.

γ^*-π azimuthal correlations in pA

A. Staśto *et al.*, Nucl. Phys. A **904-905**, 837c (2013)



In pA for $p_T^g \to 0$ dipole gluon distribution at small-x as well as the cross section vanish.
Quark, in order to radiate photon, has to acquire its p_T via multiple scattering with gluons
$\Rightarrow$ double peak structure on the away side $\Delta\phi = \pi$ appears

[A. Staśto *et al.*, Phys. Rev.D **86**, 014009 (2012)].

G^*-h azimuthal correlation function $C(\Delta\phi)$

- Azimuthal correlations between dilepton and hadron are investigated using coincidence probability per trigger particle G^*:

$$\boxed{C(\Delta\phi) = \frac{2\pi \displaystyle\int_{p_T, p_T^h > p_T^{\rm cut}} dp_T p_T \; dp_T^h p_T^h \; \frac{d\sigma(pp \to hG^* X)}{dY dy_h d^2 p_T d^2 p_T^h}}{\displaystyle\int_{p_T > p_T^{\rm cut}} dp_T p_T \; \frac{d\sigma(pp \to G^* X)}{dY d^2 p_T}}}$$

  where $p_T^{\rm cut}$ is the experimental low cut-off on transverse momenta of dilepton and hadron h and $\Delta\phi$ is the angle between them.

- To describe interactions of the incoming quark with the target color field we employ unintegrated gluon distribution function

  $F(x_g, k_T^g) = [\pi Q_s^2(x_g)]^{-1} \, exp(-k_T^{g^2}/Q_s^2(x_g)) \, , Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$ [1]

- KKP [2] fragmentation function $D_{h/f}(z_h, \mu_F^2)$ of a quark with a flavor f into a neutral pion $h = \pi^0$ was used.

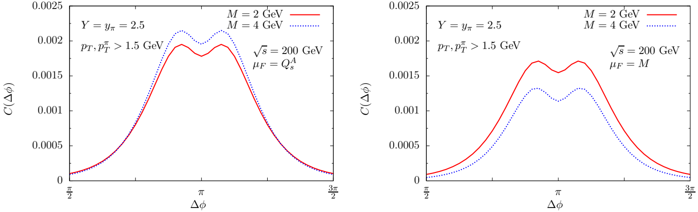
---

[1] $Q_0^2 = 1$ GeV^2, $x_0 = 3.04 \times 10^{-4}$, $\lambda = 0.288$ and $\sigma_0 = 23.03$ mb were obtained from the fit to the DIS data.

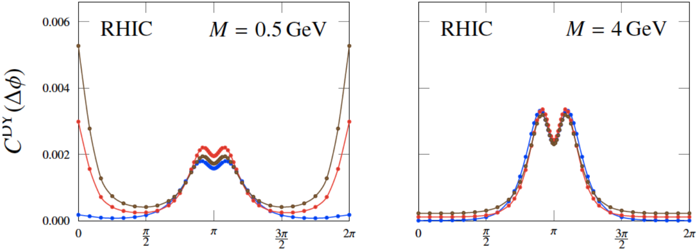
[2] B. A. Kniehl, G. Kramer and B. Potter, Nucl. Phys. B **582**, 514 (2000).

γ^*-π azimuthal correlations in dAu @ RHIC

E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

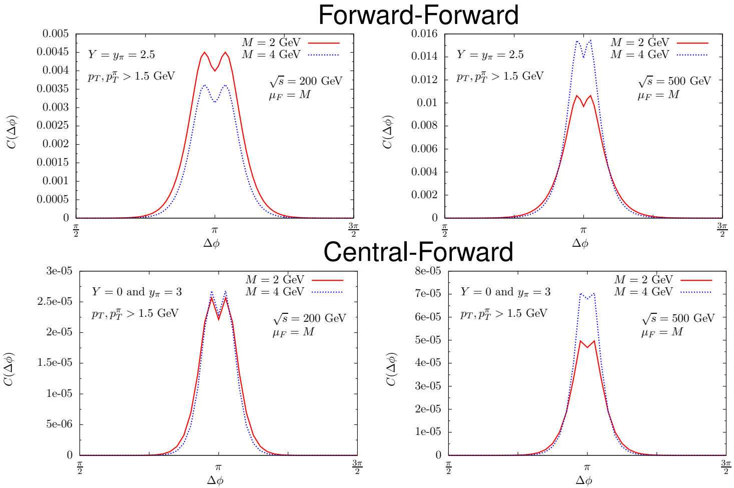


A. Staśto et al., Nucl. Phys. A 904-905, 837c (2013)



- Similarly to Staśto *et al.* the away-side double-peak structure shows up in dAu.
- Independently of the factorization scale μ_F choice $\Rightarrow$ it is expected also for pp.

γ^*-π azimuthal correlations in pp @ RHIC energies

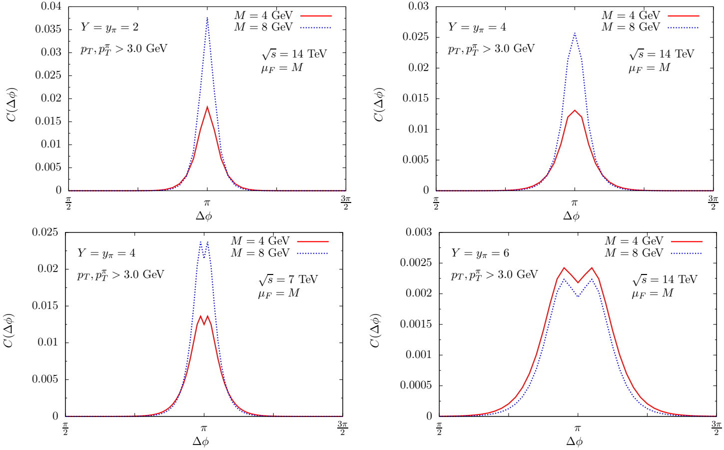


E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)

- Away-side double-peak present also in pp collisions at RHIC.
- Shows up both in F-F and C-F correlations $\Rightarrow$ measurable!
- C-F correlations are by two orders in magnitude smaller than F-F.

γ^*-π azimuthal correlations in pp @ LHC energies

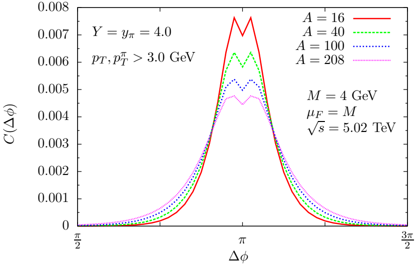
E. Basso *et. al.*, Phys. Rev. D **93**, 034023 (2016)



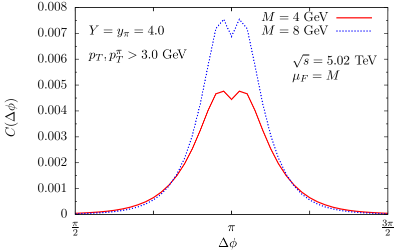
For γ^* and π close to the phase space limit double peak emerges also in *pp* @ LHC.

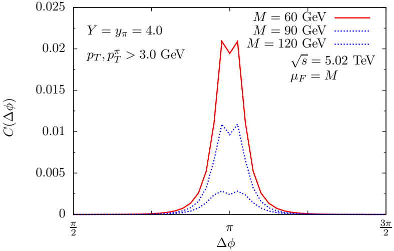
γ^*-π azimuthal correlations in pA @ LHC energies

E. Basso *et. al.*, arXiv:1603.01893 [hep-ph]



Increasing *A* smears the back-to-back pattern and suppresses the away-side peak.





In pPb a double-peak structure shows up also for the large invariant masses.

Dipole Color Singlet Model of Quarkonium Production

Heavy quark pair production in the dipole framework

- Replacing γ^* with gluon one can describe $G_a + p\,(A) \to q\bar{q}$, ($q = c, b, t$; $a = 1, \ldots, 8$) as a splitting $G \to q\bar{q}$ into heavy quark dipole. Interaction with the color field of the target then releases these heavy quarks [1].

$$\boxed{\frac{d\sigma(Gp \to q\bar{q} + X)}{d \ln \alpha} = \int d^2\rho \, |\Psi_{q\bar{q}}(\alpha, \rho)|^2 \; \sigma^p_{q\bar{q}}(\alpha\rho, x)}$$

$\Psi_{q\bar{q}}(\alpha, \rho)$ – LC wavefunction giving rate of $G \to q\bar{q}$, can be calculated perturbativelly:

$$|\Psi_{q\bar{q}}(\alpha, \rho)|^2 = \frac{\alpha_s}{2\pi^2}\left[m_q^2 K_0^2(m_q\rho) + (\alpha^2 + (1-\alpha)^2) K_1^2(m_q\rho)\right]$$

$\sigma^p_{q\bar{q}}$ – dipole cross section for inclusive (singlet + octet) $q\bar{q}$ production (GBW form):

$$\sigma^p_{q\bar{q}} = \sum_{S=1^-,8^\pm} \sigma^S_3 = \frac{9}{8}\left[(\sigma_{q\bar{q}}(\alpha\rho) + \sigma_{q\bar{q}}((1-\alpha)\rho)\right] - \frac{1}{8}\sigma_{q\bar{q}}(\rho)$$

- In Born approximation dominant contribution to inclusive production, both in open charm and P-wave quarkonia production channels, are:

[1] J. Raufeisen, J. C. Peng, Phys. Rev. D **67**, 054008 (2003)

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$$\boxed{\frac{d\sigma(Gp \to q\bar{q} + X)}{d\ln\alpha} = \int d^2\rho\, |\Psi_{q\bar{q}}(\alpha,\rho)|^2\, \sigma^p_{q\bar{q}}(\alpha\rho, x)}$$

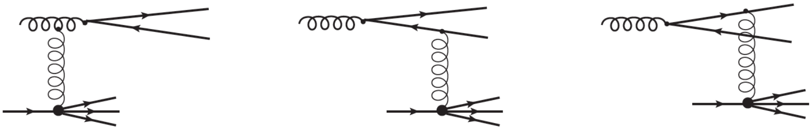
$\Psi_{q\bar{q}}(\alpha,\rho)$ – LC wavefunction giving rate of $G \to q\bar{q}$, can be calculated perturbativelly:

$$|\Psi_{q\bar{q}}(\alpha,\rho)|^2 = \frac{\alpha_s}{2\pi^2}\left[m_q^2 K_0^2(m_q\rho) + (\alpha^2 + (1-\alpha)^2) K_1^2(m_q\rho)\right]$$

$\sigma^p_{q\bar{q}}$ – dipole cross section for inclusive (singlet + octet) $q\bar{q}$ production (GBW form):

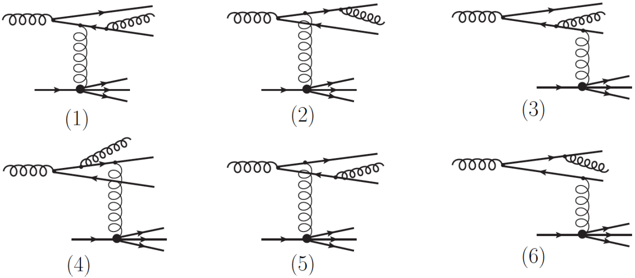
$$\sigma^p_{q\bar{q}} = \sum_{S=1^-,8^\pm} \sigma_3^S = \frac{9}{8}\left[(\sigma_{q\bar{q}}(\alpha\rho) + \sigma_{q\bar{q}}((1-\alpha)\rho)\right] - \frac{1}{8}\sigma_{q\bar{q}}(\rho)$$

- In Born approximation dominant contribution to inclusive production, both in open charm and P-wave quarkonia production channels, are:



Dipole Color Singlet Model of $pp \to \{q\bar{q}\}_{1^+} + X$

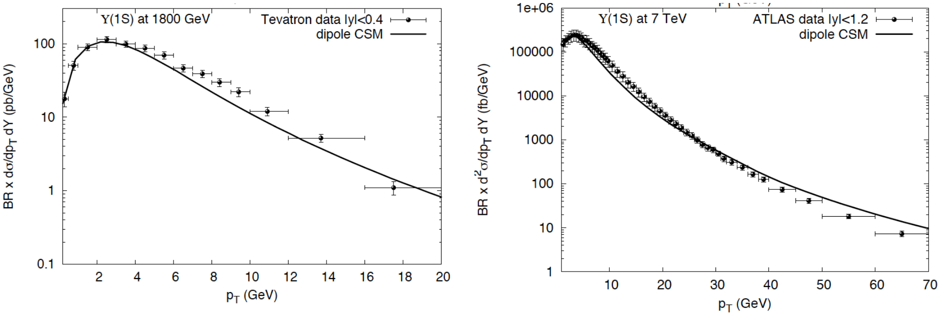
- LO contribution to C-odd S-wave quarkonium production goes beyond simple Born approximation and is due to extra gluon emission off the produced heavy quark $q\bar{q}$ pair state*.



- Diagrams (5) and (6) with real gluon emission off a quark different from that coupled to the t-channel gluon are suppressed.

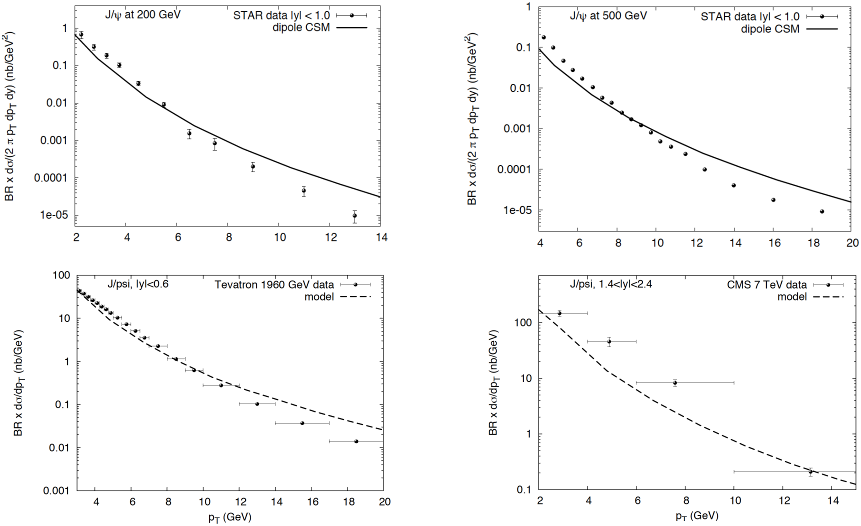
*) To produce $\{q\bar{q}\}_{1^+}$ state at least 3 gluons need to be coupled to the quark line.

$\Upsilon(1s)$ production in pp collisions: preliminary results



$d\sigma/dp_T dY$ - spectra of $\Upsilon(1s)$ at mid-rapidity, from Tevatron (left) and LHC (right).
CDF: Phys.Rev.Lett. 88 (2002) 161802, ATLAS: arXiv:1211.7255 [hep-ex]

J/ψ production in pp collisions: preliminary results



Transverse momentum spectra of J/ψ at mid-rapidity, from RHIC (top), Tevatron (bottom left) and LHC (bottom right).
CDF: Phys. Rev. Lett. 79, 572 (1997), CMS:arXiv:1111.1557 [hep-ex], STAR: arXiv:1208.2736 [nucl-ex]

$\{q\bar{q}\}_{1^+}$ production in association with a gluon

- In the dipole picture incoming gluon moves along the z-axis.
  $\Rightarrow$ use collinear gluon PDF $xg(x,\mu^2)$ with $k_\perp$-distribution of projectile gluon implicitly integrated out [1]:

$$\frac{d\sigma^{pp}_{incl}}{dY d\alpha} = x_1 g(x_1,\mu^2)\frac{d\sigma(Gp \to q\bar{q} + X)}{d\alpha}, \; \mu^2 \approx M^2_{q\bar{q}} = \frac{m_q^2 + k_{12}^2}{\alpha(1-\alpha)}$$

  $\Rightarrow$ p_T-distribution of heavy quarkonia is generated by ISR and FSR only.

- Momentum transferred by color background field of the target proton to collinearly moving gluon with $k_{1\perp} = 0$ is predominantly longitudinal one (exchanged gluons have typically soft transverse momenta $k_{2\perp} \sim m_g$).
  $\Rightarrow$ In the perturbative limit $k_3 \gg m_g$, by momentum conservation transverse momentum of $\{q\bar{q}\}_{1^+}$ quarkonium is close to that of the radiated gluon $\vec{p}_T \approx -\vec{k}_3$.

  $\Rightarrow$ Transverse momentum correlation between J/ψ, $\psi(2s)$, Υ and associated (semi-hard) hadron from the fragmentation of the third gluon is expected.

[1] B. Kopeliovich *et al.*, Nucl. Phys. A **696**, 669 (2001)

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Conclusions and Outlook

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- The dipole formalism of DY production of gauge bosons and quarkonia was presented.
- Parameter-free calculations of J/ψ and Υ differential transverse momentum cross section performed within dipole CSM approach provide substantial improvement over previous CS NLO calculations.
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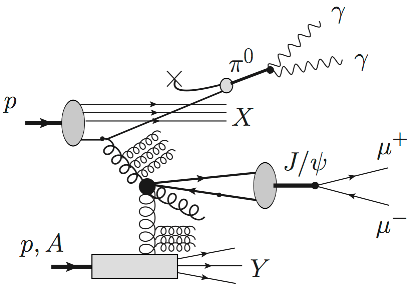
Outlook

- Color dipole approach was also used to study suppression of high-p_T forward hadrons in dAu collisions at RHIC [1].
- Joining forward hadron with mid-rapidity quarkonium production $\Rightarrow$ forward-central correlations in *pp* and *pA* – feasible at RHIC.



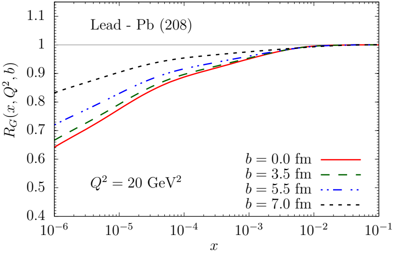
- New class of measurements will reduce backgrounds and uncertainties in quarkonium production in *pp*/*pA*; will allow to test h.o. pQCD effects and disentangle them from CGC and other multi-particle effects.

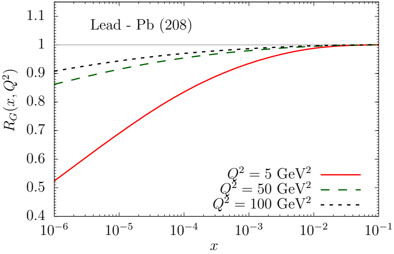
[1] J. Nemchik, *et al.*, Phys. Rev.C **78**, 025213(2008), Nucl. Phys. A **830**, 611C (2009), PoS ICHEP2010 (2010) 354.

Back up slides

Color dipole description of pA collisions

- $\sigma^N_{q\bar{q}}(\rho,x) \to \sigma^A_{q\bar{q}}(\rho,x) = 2\int d^2b \left[1 - \exp\left(-\frac{1}{2}T_A(\mathbf{b})\sigma^N_{q\bar{q}}(\rho,x)\right)\right]$
- Gluon shadowing: $\sigma^N_{q\bar{q}}(\rho,x) \to \sigma^N_{q\bar{q}}(\rho,x)\, R_G(x,Q^2,\mathbf{b})$ leads to additional nuclear suppression in production of DY pairs at small x in the target. R_G - ratio of the gluon densities in nuclei and nucleon - was derived in [1]





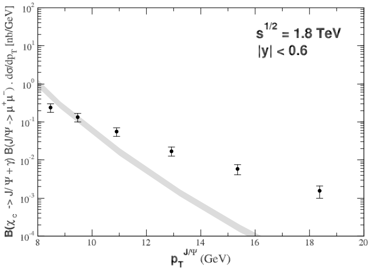
- Initial-state energy loss suppression of nuclear PDFs at the kinematical limits [2]:

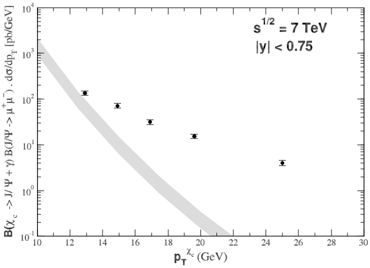
$$q_f(x,Q^2) \to q_f^A(x,Q^2,b) = C_v\, q_f(x,Q^2)\, \frac{e^{-\xi\sigma_{\rm eff}T_A(b)} - e^{-\sigma_{\rm eff}T_A(b)}}{(1-\xi)(1-e^{-\sigma_{\rm eff}T_A(b)})}$$

[1] B.Z. Kopeliovich *et al.* Phys. Rev. **D62**, 054022 (2000); ibid C**65**, 035201 (2002), J. Phys. G**35**, 115010 (2008).

[2] B.Z. Kopeliovich *et al.* Phys. Rev. C**72**, 054066 (2005); Int. J. Mod. Phys. E**23**, 1430006 (2014).

$pp \to \chi_c \to J/\psi$ (preliminary results)





Transverse momentum spectra of J/ψ at mid-rapidity, Tevatron (left) and LHC (right).
CDF: Phys. Rev. Lett. 79, 572 (1997), Atlas: JHEP 07 (2014) 154